Extension of PIV methods

PISAREK Jerzy[1,a*]

[1]Kiedrzyńska 95 m 20, POLAND

[a]jerzy.pisarek@gmail.com

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Abstract. The process of the measurement of the fluid speed by use of PIV method consists most often of several stages: the insertion of the fluid markers of movement, the stimulation of these markers to lucency, the registration of the image of markers, the quantitative analysis of registered images for the purpose of finding the parameters of their movement. Every one of these stages can be realized in many ways. This creates the possibility of adjustment of the measuring-process to realized exploratory tasks. The present article shows possibilities existing in this area, significantly transcending the offer of producers of the measuring apparatus dominant on the market. Additionally, sources of measuring errors ignored usually in manuals of commercial equipment sets are evidenced.

Introduction

Acronym PIV means Particle Image Velocimetry. In the classical version of the method small shiny particles, e.g. solid phase particles, are inserted into the fluid. These particles move together with the fluid, constituting the marker of the movement. Two (or more than two) photographs of the particles images registered in the determined time interval (fig. 1a) enable to determine the speed field in considered area.

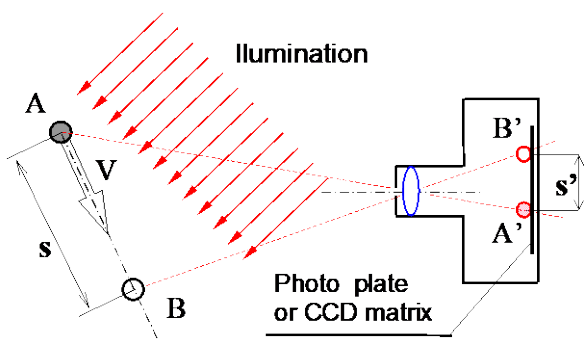

Fig. 1a. Registration of particle image

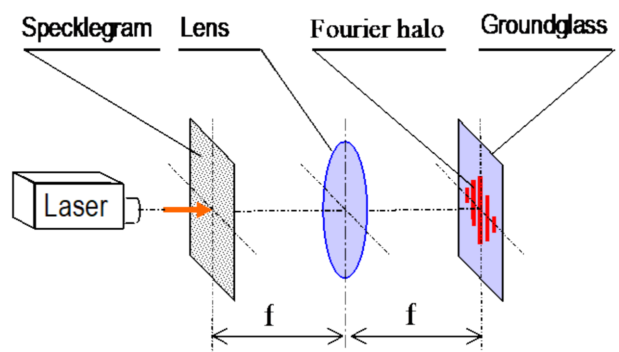

Fig. 1b. Analysis of registered image by use of point by point optical Fourier processor

There are many different kinds of particles, different manners of excitation them to lucency, different techniques of registration of the particle image and different manners of the analysis of image displacement. Classification of certain variants of PIV method elements is presented in table 1.

Tab.1. Multiple variants of components of PIV measuring process

	Element of PIV Method	Variants	Marginalia and remarks
1	Marker	Solid body particle: balsa dust, microbalon, flaky aluminum, toner of laser printer Aerosol (in gas media) bubbles of gas in liquid bubbles of gas in gas visible in extended laser beam or in Talbot interferometer	In great deal of commercial offers of PIV arrangement a oil aerosol is very often used as the marker
2	Kind of illumination	Frontal lighting: coherent, noncoherent Lighting from behind: coherent or not coherent Monochromatic optical knife: coherent, noncoherent, Multicolour optical knife Photorescence or luminescence High temperature lighting	Optical knife based on laser light is most often used. Variant "c" in connection with strobing and variant "d" give possible to determine component of speed perpen-dicular to plane of the light knife.
3	Kind of registration	On photoplate or on CCD matrix Holographic By use of classical single aperture lens By use an photo-objective with stationary or rotating multihole apertures In different interferometer systems	Almost all equipment for PIV used a CCD (charge coup-led device) matrix. The 3D holographic registration was used in TU of Częstochowa by J.Szafrański.
4	Exposure	Registration on following different frames Two short exposures on one frame Multiexposures on one frame Strobing Exposure in with strongly controlled time Time averaging Amplitude or colour modulated impulse	In commercial applications variant "a)" dominates. Time to time variant "b" is used. Variant "g" was developed in TU of Częstochowa by J.Pisarek, A.Wojciechowski, and P.Mirek
5	Whole field image analysis	Many kinds of analog whole field Fourier processors Application of moire effect Digital Fourier processing, binary filtering and interference of images	Whole field analysis is for today used in to advertising and educational purposes
6	Point by point image analysis	Application of point by optical point Fourier processor Classical digital correlation and autocor-relation Differential correlation Approximation methods, direct determi-nation of components of the relative movements tensor	Techniques based on integral transformations (variant b and c) can be applied only for great quantity of markers in analysed area.

There exist several hundred different configurations of elements constituting the measurement process by use of PIV methods**.** Unfortunately only several are applied in practice. This results from the strong tendency to the application only of commercial sets of measuring arrangements and proposed by their producers methods of experimental research. The knowledge of persons working in area of the experimental mechanics of fluids is very often restricted to commercial offers of several domineered market companies. It determines the exploratory possibilities in essential way. For purpose of presented article is visible, that the possibility of the significantly better adjustment of the applied methodology of the measurement to the kind of realized tasks exists. It is necessary reaching to wider knowledge about the theory of experiment and exit out solutions proposed by producers and sales agents of the measuring equipment.

Historic conditionings

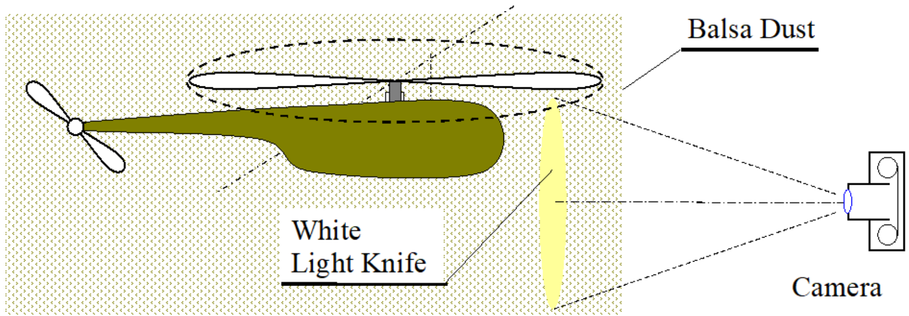

Fig 2. Investigation of the real flow inducted by helicopter rotor, described in NACA reports

The first information of PIV application comes from 50-th years of XX century. As the indicator of the movement of powdered wood of the balsa was applied. Suitably formed geometrically and amplitudely modulated beam from antiaircraft searchlight was a source of the light **.** Images of dust particles on the classical film plate were registered. In these times presently applied methods of image analysis were still not known. Presently applied phraseology was not used too. Registered film cadres were analysed manually. The army was not interested in a publication of its results in the commercial scientific literature. Therefore the world of the commercial knowledge of new measuring techniques did not notice this new measuring techniques. The dam of the ignorance was broken in the year 1982 when E.Brnaben, J.C.Amare, M.P.Anogo [1] used techniques PIV in laboratory-research and made available results of their works in the English-speaking, high-publishing journal.

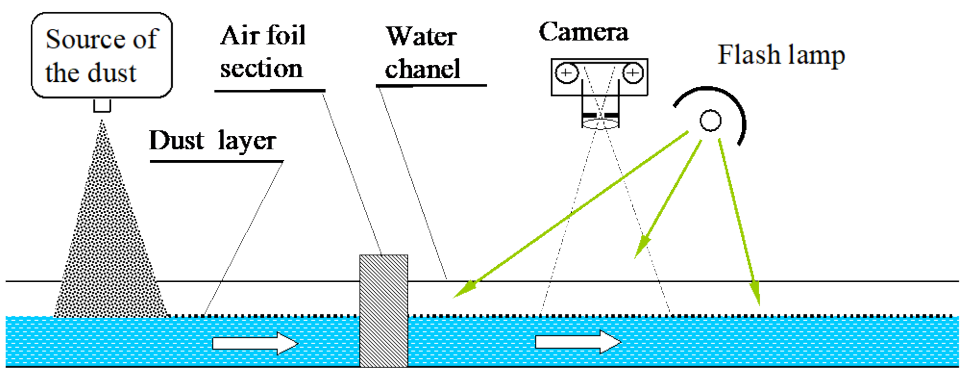

Fig.3. The use of the PIV technique to the investigation of flat flows in the open channel.

As the marker of the movement the aluminum-dust which remained on the water surface as the result of the surface tension was applied. Of course also markers from material with specific gravity smaller than the specific gravity of liquid were possible to use. Molecules of the dust were illuminated from above.

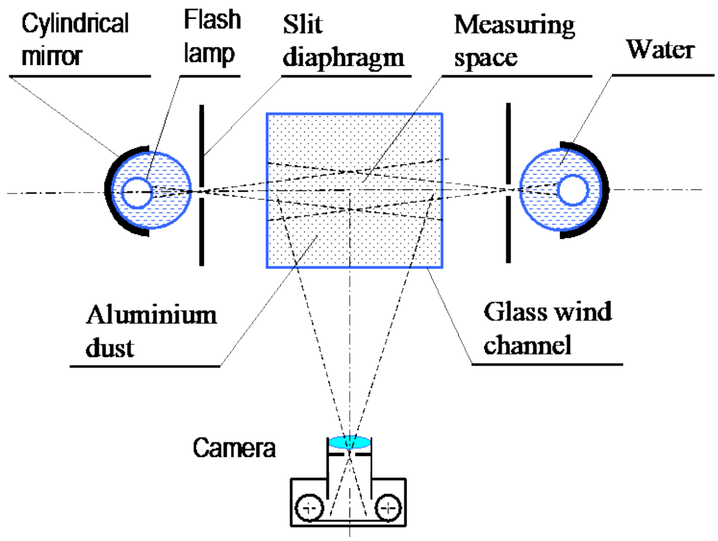

Fig.4. Two white light knife arrangement for registration of the air speed in the wind tunnel

In 1986 J.Pisarek [2] presented the proposal of the measurement of the speed of the fluid in the glass-wind tunnel. The aluminum-pigment was used as the marker. Two light-knives were built on the basis of high voltage bar-flash, applied usually in impulse lasers. In the eighties any descriptions of the equipment PIV the use of laser light knife were presented in many publication 1n year 2001 J.Pisarek and A.Wojciechowski proposed [3] the computerly controlled amplitude modulation of the laser radiation (Fig.5b).

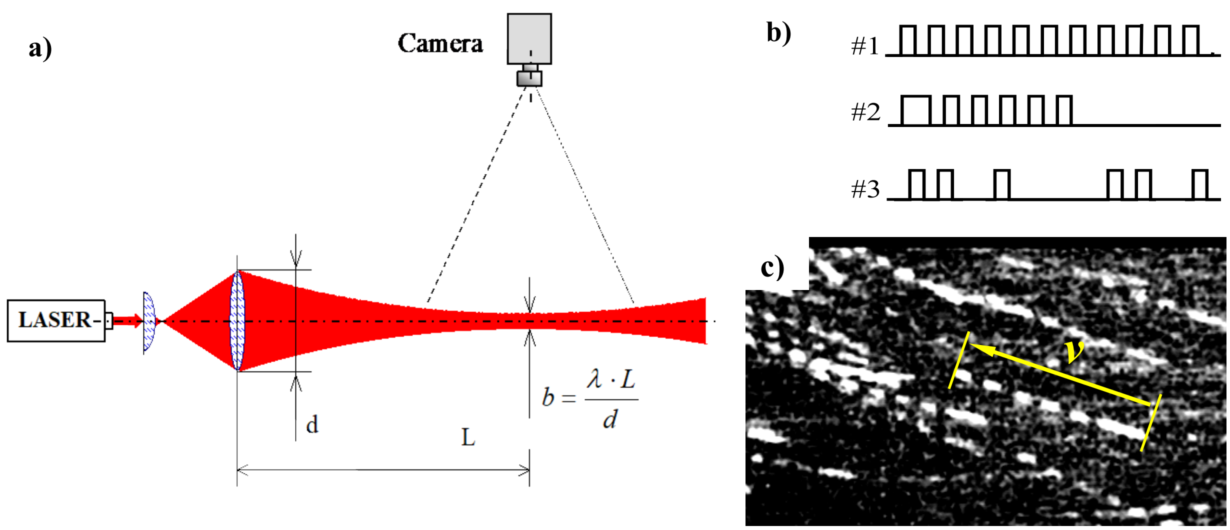

Fig.5. The use of the laser- light-knife with time modulated power

a) the geometry of the knife (where λ is the wavelength of light)
b) examples of graphs of function of light amplitude modulation
c) the image observed at the modulation with the course #2

This gave the possibility of the increase of measuring precision and possibility of designation of sense of a velocity vector on the base of only one film frame. The use of strobing at the large thickness of the light-knife [4,5,6] or at the multicoloured knives gave the possibility of determination of the third constituent of the velocity. The laser beam is a gaussian beam which properties are described in handbooks of the wave-optics [9,10]. The laser optical knife is one of forms of transformation of the gaussian beam. By selection of suitably parameters of the optical system one can, for the determined wavelength, fix the average thickness of the knife and his width and to enumerate changes of these parameters in the area of measuring.

The registration of the picture of particle constituting the marker of the movement surrounding fluid can be made by the camera lens with single-hole or multihole aperture diaphragm.

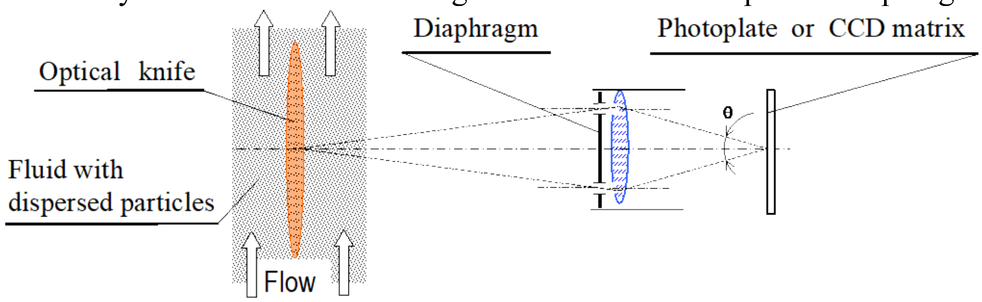

Fig. 6. The registration of particles image by the lens with the two-hole aperture diaphragm

In this second case (fig.6) in the plane of the picture the row of interferential fringes is observed. Fringes are perpendicular to the straight line passing trough holes in the diaphragm and distant each from other is inversely proportional to the length of the distance between these holes. If on material with the strongly non-linear attenuation diagram two different positions of the particle in the small distance will be registered then the interference of images (moire effect) will be observed. The same effect will follow in case of the digital processing of the image registered on linear material transformed in to B&W image. In case of the peck of simultaneously registered particles moving in the same direction with different speeds we will receive the contour-map of the speed component parallel to the line connective diaphragm holes.

Analog Fourier processors

Idea of point by point processor was presented on fig.1b. In practice the optical system can be extended a little more. The theory of optical Fourier transforming is described in the work [10].

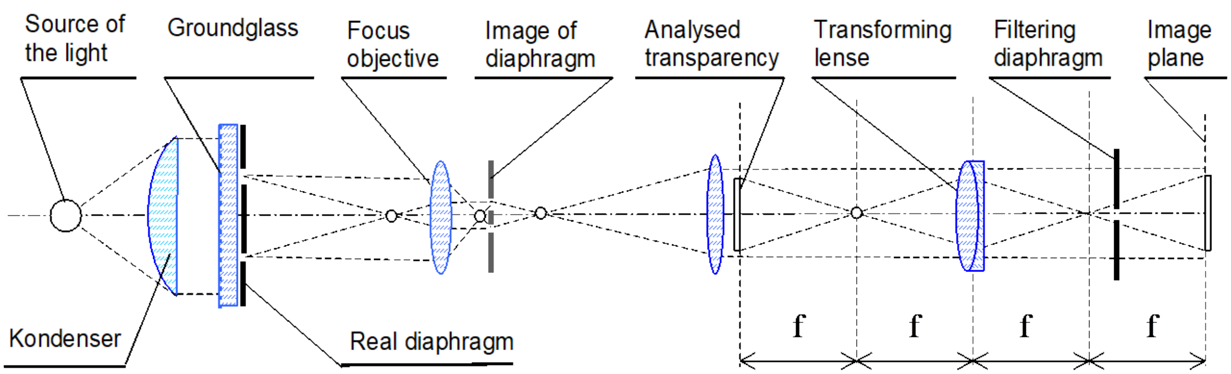

Fig.7. The diagram of optical Fourier processor to determining of the speed module.

Whole field processing of PIV image and the theory of Fourier transformation of multiexposure speckle images, (to which PIV images belong), are described in work [7]. New solution, hitherto not published, is the processor enabling the visualization of the spatial schedule of modules of the speed (fig.7) . The light source of containing the diaphragm with at least one annular (ring) hole is a characteristic feature of proposed arrangement. The hole in the diaphragm can be filled by a circular-symmetrical multicoloured filter or to contain a circular-symmetrical grating. The filtration of spatial frequencies of analysed transparency takes place by the small single hole situated centrally in the plane of transforms.

Digital analysis of the image

The algorithm of the quick two-dimensional fast Fourier transformation (FFT) is currently very often used technique of multi-exposure particle image analysis. If in the virtual transform plane the binary filter will be put and the reverse transform of the function modified by this filter will be

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made then the contour-map of the determined speed component on whole field measuring region will be possible to obtain. This is the digital implementation of whole field optical Fourier processors.

For point by point analysis of the speed, recorded trough PIV technique the correlation or autocorrelation algorithms can be used. In most cases there are product-algorithms.

Let us assume that two different frames with registered two images are translocated in relation to themselves \by vector **s**=[s_x, s_y]. Function $K_1(u,v)$ described by the equation (1) reach a maximum when $|u|=|s_x|$ and $|v|=|s_y|$.

$$K_1(u,v) = \iint_A J_1(x,y) \cdot J_2(x+u, y+v)\ dx\,dy = \max \tag{1}$$

when

- x,y – Coordinates in plane of analysed image
- u,v – Coordinates in virtual plane in space of integral translation
- A – Analysed area of the image
- J(x,y) – The function of the brightness of points of images registered in the first or second exposure

In case of when both images are registered on the same film frame the functional K2 described by formula 2 achieves the maximum when $|u|=|s_x|$ and $|v|=|s_y|$

$$K_2(u,v) = \iint_A J(x,y) \cdot J(x+u, y+v)\ dx\,dy = \max \tag{2}$$

In case of registration of N-exposures the absolute value of the shift of analyzed image region one can obtain from the condition of the maximization of the functional value:

$$K_3(u,v) = \iint_A \prod_{n=0}^{N} J(x+n\cdot u, y+n\cdot v)\ dx\,dy = \max \tag{3}$$

Differential algorithms give a radical improvement of accuracy of calculations. In case of N exposures sought module of movements component can be obtained by seeking the minimum of functional:

$$K_4(u,v) = \sum_{n=1}^{N} \iint_A \left(J(x+n\cdot u, y+n\cdot v) - J(x,y)\right)^2 dx\,dy = \min \tag{4}$$

Given algorithms permit the designation from one film frame of only absolute values of movement components. However the possibility of the designation of the speed sense exists if we apply the suitable modulation of laser pulse. For example for modulation #3 from fig.3b the sense of the velocity vector one can obtain designating the maximum of the function:

$$K_5(u,v) = \iint_A \left(\left(J(x,y)\right)\cdot\left(J(x+u, y+v)\right)\cdot\left(J(x+3u, y+3v)\right)\right)\ dx\,dy = \max \tag{5}$$

Described higher algorithms are intended to the analysis of the speed of the fluid in which the large volumetric concentration of markers is observed. In case of small concentrations of particles and in case of some kinds of multi-phase flows one ought to apply algorithms basing an analysis of trajectory given out particle. The use of the theory of cliques gives here good results.

Atypical uses

A spectacular example of the use of the technique PIV is technique of analysis of traffic of solid body particles in thick fluidal layer, elaborated in TU Częstochowa by K.Sikora and J.Pisarek. The modelling of the fluidal-layer by the set of identical particles with a very dark or

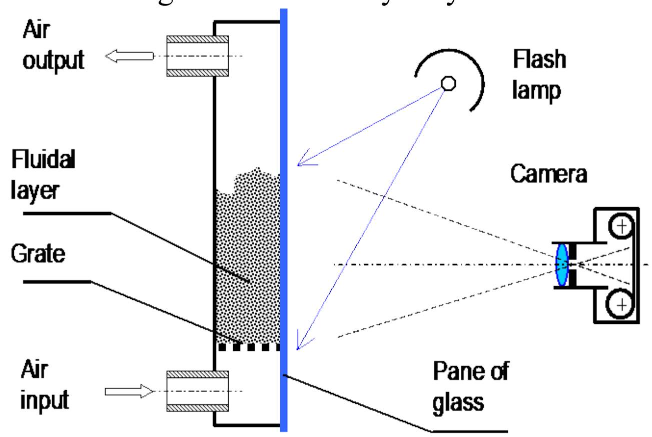


Fig.8a. Configuration of statement for measuring of *processes in high dense fluidal layer*

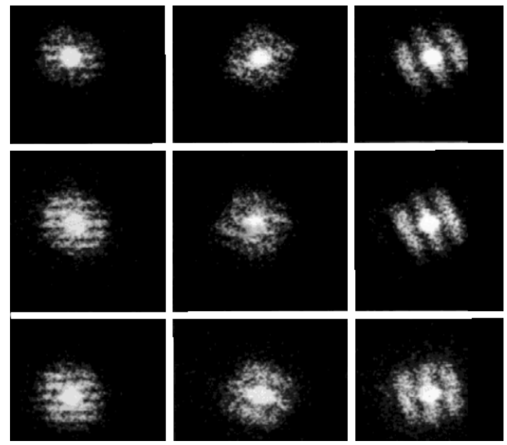
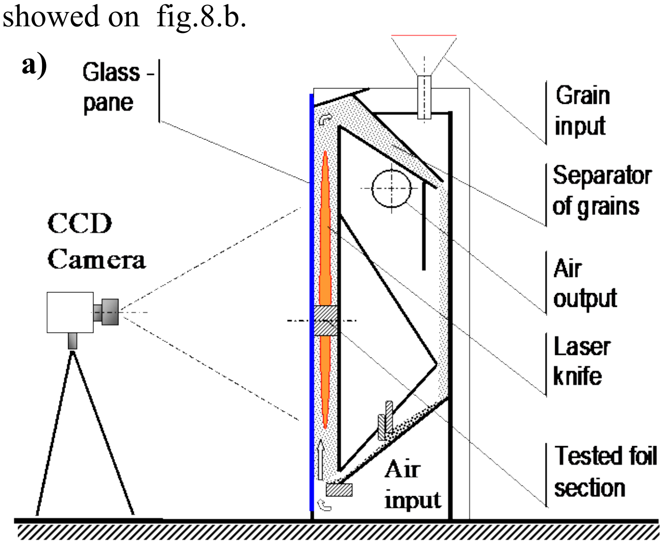


Fig.8b. Fourier halos obtained in optical point by point processor from transparency recorded in arrangement shown on fig. 8a

very bright colour is a general idea of this technique. Number of bright particles should be at most 5-times smaller than number of dark particles. The diagram of the measuring-arrangement one showed on fig.8a. The example of result of the analysis in point by point Fourier processor is showed on fig.8.b.

a)



b)

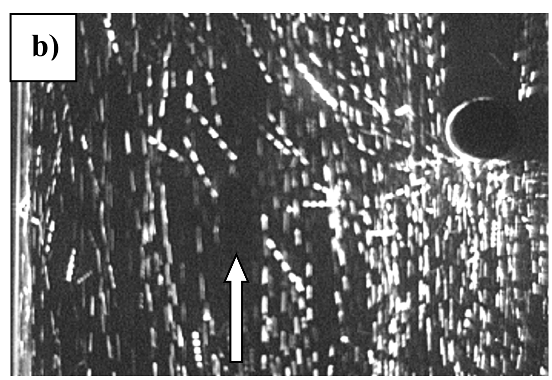


Fig. 9.
a) *Desk table wind table tunnel*
b) *The fragment of typical image registered from this tunnel*

The PIV technique can be applied also to model investigation of circulation fluidal layers and to the illustration of some phenomena of the mechanics of fluids. The transportable arrangement is made from glass and has dimensions1000x400x200 mm. The schema of tunnel is shown on fig.9a. The air flow was forced by usual vacuum cleaner. As particles of the solid phase alternatively: the table salt or sand (for two phase flow) , the semolina (for gas flow visualization) were applied.

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Disadvantages and errors

The basic disadvantages of PIV methods is the lack of the possibility of making a measurement in real-time. The inertial reaction and the gravitation can influence on the particle equally strongly as surrounding her gas. Additionally electrostatic forces can be significantly sources of measuring errors. The movement of speckle pattern generated in laser light by the gyral solid body particle is also often observed source of error.

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